Cognitive Radio Experimentation World

Project Deliverable D4.3

Definition of Test Scenarios and Benchmarks for VESNA Testbed

Contractual date of delivery:	29-02-12
Actual date of delivery:	29-02-12
Beneficiaries:	JSI
Lead beneficiary:	JSI
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Workpackage:	WP4 – Benchmarking and Federation
Estimated person months:	3
Nature:	R
Dissemination level:	PU
Version	0.6

Abstract: This document complements the CREW deliverable D4.1 by describing the test configurations that have been constructed for the VESNA-based testbed and providing the baseline framework for experimenters to build relevant benchmarks for a particular use case within the respective usage scenario. This will allow full integration of the VESNA-based testbed in the CREW federation, provide means to accurately reproduce and replicate the experiments, as well as compare the results obtained from different experiment setups at the same testbed or experiment runs at several testbeds of the CREW federation. Detailed benchmarks are to be specified following this document based on relevant field experiences obtained during the initial trial experiments.

Keywords: benchmarking, usage scenario, experimentation, testbed, VESNA, LOG-a-TEC

Revision History

1.0	Mihael Mohorcic JSI	Incorporated internal reviewers' comments, final formatting	29 Feb 2012

Executive Summary

This document amends the CREW deliverable D4.1 by describing the test configurations and benchmarks from the perspective of the VESNA-based testbed that is complementing the original four CREW testbeds. To this end the document is focusing on the test configurations and benchmarks for the three usage scenarios (US) and respective use cases (UC) that were identified as suitable for the VESNA-based testbed. In particular, these are context awareness for cognitive networking (US1), horizontal resource sharing in ISM band (US3), and cooperation in heterogeneous networks in licensed bands (US4).

The document first provides a description of the building blocks of the VESNA-based testbed that enable both the local testbed operation as well as its remote control and integration in the CREW federated platform. These building blocks include: (i) VESNA and USRP sensor nodes deployed in the LOG-a-TEC outdoor experimental wireless sensor network testbed; (ii) appropriate spectrum sensing software application; (iii) GRASS-RaPlaT tool for storing results in GIS database, visualisation of the results and determination of the interference regions; and (iv) reliable procedures for over-the-air (OTA) reprogramming and experimental data collection. Over the air programming is necessary in remote testbeds in which there are no other means of deploying new software on devices. The need of reprogramming requires additional configuration parameters to ensure that the software running on the devices is uniquely identified and thereby available for fair comparison of different experiment results. For data collection in remote testbeds, unique performance metrics have been defined, to help the users design the experiments and understand the specifics as well as limitations of a testbed. When the goal of an experiment is to test a new communication protocol or system, the same metrics can be applied for describing the new protocol as the ones that have been used in the testbed's description.

Next, the document provides test configurations and the baseline framework for benchmarks that have been developed for internal USs on the VESNA-based testbed. These are:

- Radio environment sensing in ISM and TV bands, where the aim is to gather the information about the actual occupancy of the selected frequency range by existing or purposely deployed transmitters.
- Horizontal spectrum sharing between heterogeneous networks in the ISM bands focusing on the outdoor operating environment, where the aim is to realistically characterize the outdoor ISM environment and enable the study of different coexistence, cooperation and spectrum sharing strategies.
- Coexistence between primary and secondary users in licensed TV bands, aiming at reliable characterisation of spectrum usage. Subsequently these measurements will be used in computer simulations or, if a test and trial licence is obtained, in field experiments using USRP software radio platforms as transmitters.

Configuration parameters and performance metrics defined by the benchmarks will ensure the reproducibility of the UCs within each US and seamless comparison of the results from different instances of an experiment carried out on the same or different hardware and software.

List of Acronyms and Abbreviations

CN	Cognitive Networking
CR	Cognitive radio
CREW	Cognitive Radio Experimentation World
GIS	Geographic Information System
GRASS	Geographic Resources Analysis Support System
GSM	Global System for Mobile Communications
ISM	Industrial, Scientific and Medical
JSI	Jozef Stefan Institute
LOG-a-TEC	Outdoor Wireless Sensor Network testbed in the city of Logatec (Slovenia)
OTA	Over-the-air (reprogramming)
PFA	Probability of False Alarm
PMD	Probability of Missed Detection
RaPlaT	Radio Planning Tool
REM	Radio Environmental Map
RFID	Radio Frequency Identification
ROC	Receiver Operating Characteristic
RSSI	Received Signal Strength Indicator
TETRA	Terrestrial Trunked Radio
TV	Television
TVWS	Television White Space
UC	Use Case
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications System
US	Usage Scenario
USRP	Universal Software Radio Peripheral
VESNA	VErsatile platform for Sensor Network Applications
VHF	Very High Frequency (30…300 MHz)
WSN	Wireless Sensor Network

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1. Introduction

The CREW project is establishing a federation of cognitive radio network testbeds and creating a benchmarking framework to facilitate repeatable experimentation on cognitive radio and dynamic spectrum access for a broad range of test cases. The aim is to define test configurations, methodologies and performance metrics so as to increase the reproducibility of experiments and comparability of results obtained in use cases at the same or at similar testbeds.

In order to facilitate full integration of the VESNA-based testbed in the CREW federation (by also adopting the CREW benchmarking framework), suitable test configurations and benchmarks need to be defined, however taking into account the specifics of the testbed deployment in real-life outdoor environment with limited capability of controlling the background radio environment. This document thus complements the test configurations and benchmarking guidelines defined by other CREW partners in deliverable D4.1 [1], with respect to the VESNA-based testbed provided by JSI. The focus is on the three usage scenarios (US) and belonging use cases (UC) identified in the deliverable D2.4 [2] to be supported by the VESNA-based testbed. These are context awareness for cognitive networking (US1), horizontal resource sharing in ISM band (US3) and cooperation in heterogeneous networks in licensed bands (US4). For each UC within respective US the following must be specified, to support the evaluation of new concepts as defined in WP6 [1]:

- Conditions of the deployment at the physical and network layer, such as physical topology, radio technology and background radio environment.
- A set of controlled interference sources including secondary users competing for the band that is not occupied by primary users, random (but controlled) interferers displaying no pattern and interferers with some underlying stationary pattern (e.g. cyclostationarity).
- A set of applications, in a broad sense defined as streaming media, file transfer, web applications, monitoring application, etc.

Benchmarking experiments thus require sufficiently accurate models and settings to emulate realistic traffic scenarios and interferers within a particular usage scenario. Applications and interference sources will generate specific traffic patterns, which can be modelled as a random process, parameterized by the packet arrival rate (uniform vs. bursty), packet size, average transmission rate, etc.

As described in [1], a benchmark is fully defined by:

- A test configuration, specifying the variable parameters of different models, interference sources and network setup.
- The performance metrics, specifying the parameters to be logged during a test run.

Depending on the UC, a single or multiple benchmarks can be defined. The target of the benchmark is characterising a single criterion, such as spectrum efficiency, energy efficiency, throughput or scalability or a combination of multiple criteria as for instance spectrum efficiency at a given bit error rate requirement.

In addition to the outdoor deployment, the VESNA-based testbed also consists of an indoor part, which is deployed in the premises of JSI campus and used predominantly for testing and validation of new hardware modules, algorithms and protocols before their installation in the outdoor testbed, as well as cognitive networking (CN) testbed for semi-automated and automated protocol stack composition.

2. VESNA-based Testbed Configuration

In order to fully integrate the VESNA-based testbed in the CREW federated platform the VESNA sensor nodes with appropriate spectrum sensing software application, representing the main part of the testbed, are complemented by (i) GRASS-RaPlaT tool for storing the results in a GIS database, visualisation of the results and determination of the interference regions; and (ii) over-the-air (OTA) reprogramming capability supporting remote reconfigurations of the testbed to the specifics of a particular use case. This general setup of the VESNA-based testbed is further explained in the following subsections.

2.1 LOG-a-TEC experimental wireless sensor network testbed

The VESNA-based CREW testbed, constituting one of the five federated testbeds, is being deployed in the city of Logatec, as part of a LOG-a-TEC experimental wireless sensor network (WSN) testbed. The core of the LOG-a-TEC testbed will consist of ZigBee based VESNA sensor nodes mounted on public lighting infrastructure.

For the CREW testbed, sensor nodes on light poles are being equipped with different transmitting and spectrum sensing capabilities in ISM and VHF/UHF frequency bands. The layout of fixed nodes in the outdoor environment depends on the layout of light poles. These nodes can be remotely reprogrammed, reconfigured and (re)clustered according to the needs of the investigated use case.

For the execution of particular experiments that require advanced spectrum sensing capabilities, as well as to support and provide an in-the-field reference, three USRP modules will also be deployed on fixed locations.

Fixed VESNA nodes that act as transmitters or receivers in the ISM frequency bands or as receivers in the VHF/UHF frequency bands, will be complemented with portable integrated USRP-VESNA modules, representing secondary user CR enabled terminals.

The conceptual setup of the VESNA-based testbed is depicted in Figure 1.

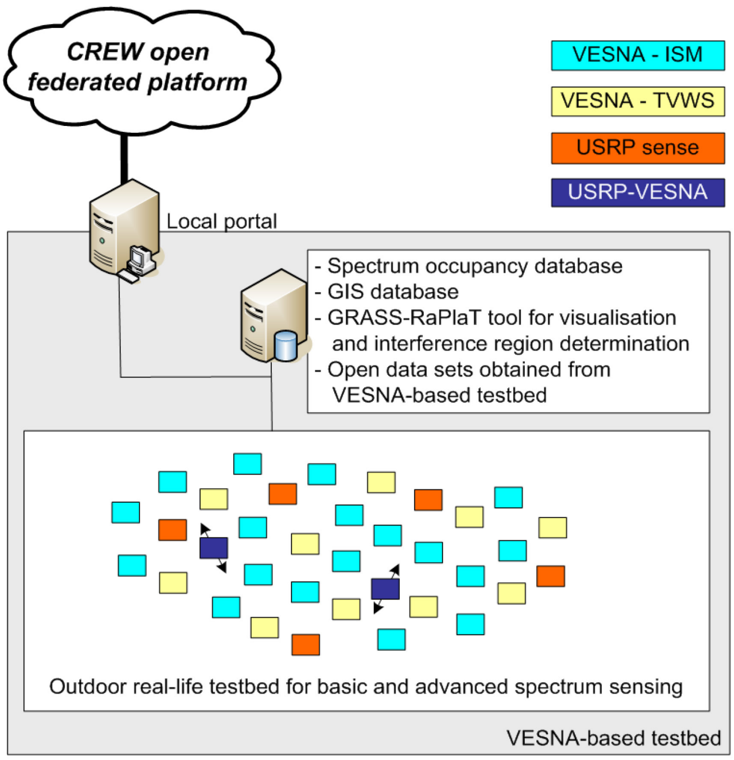

Figure 1. The conceptual setup of the VESNA-based testbed

2.2 GRASS-RaPlaT

The integration of the GRASS-RaPlaT simulation tool [5] into the LOG-a-TEC testbed is depicted in Figure 2. The LOG-a-TEC testbed is represented with a set of transmitters/receivers connected via a gateway node to the database and via the web interface to the user/experimenter. The user can access the data stored in a database, control/reconfigure the testbed, retrieve results from pre-calculated maps from the GRASS server and even request some new calculations from the GRASS and its add-on RaPlaT.

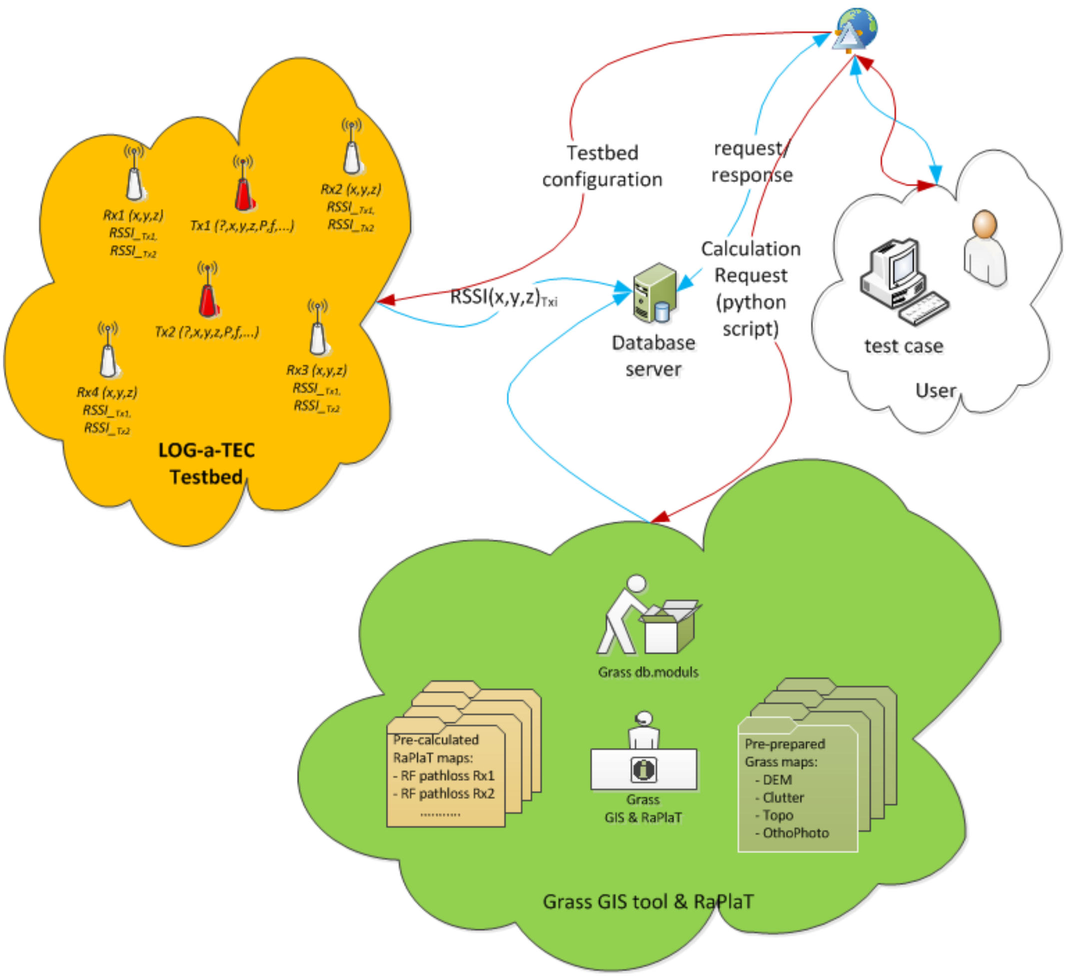

Figure 2. The integration of the GRASS-RaPlaT into LOG-a-TEC testbed

GRASS [3],[4] is one of the most widely used open source Geographical Information Systems (GIS). It operates over raster and vector data and in total comprises over 350 modules for processing, analysis and visualization of geographical data. GRASS-RaPlaT [5],[6] is an open-source add-on tool for GRASS that is being developed at JSI. By including a number of propagation channel models and a module for sectorisation according to a given antenna patterns it enables simulations of radio coverage. Additionally, it includes several modules for adapting the input data and analyzing simulation results, while its modular structure allows high degree of adaptability to user requirement. It was originally designed for radio coverage calculation of GSM/UMTS systems, but can be applied also to other wireless systems in the frequency range 400 MHz - 2.4 GHz. In this sense, its accuracy has been validated with field measurements of GSM, UMTS, TETRA and ZigBee networks, as well as by comparing with results from a professional radio network planning tool.

The GRASS-RaPlaT tool will be used in the VESNA-based testbed (i) for storing GIS data; (ii) as a tool for conversion of GIS data to the data form appropriate for visualization via the web interface;

(iii) for calculating radio environmental maps (REM) and preparation for their visualization; and (iv) most importantly, in the inverse channel modeling for interference region determination and collaborative hidden node detection.

Frequently used data, which are not varying with time, such as the path-loss of fixed receivers, digital elevation maps, clutter maps, topographic maps and ortho photo maps will be pre-calculated and stored as a GRASS data structure. Data and/or maps which are time varying, including interference regions and path-loss of mobile receivers, will be calculated on the user/experimenter request. The results from GRASS-RaPlaT operations will be stored in a database using Grass db.modules, or into geolocated raster or vector maps, appropriate for visualization via the web interface.

The GRASS-RaPlaT tool and the database server with appropriate databases form REM. REM can be viewed as an integrated database that provides multi-domain environmental information and prior knowledge for cognitive radios, such as the geographical features, available services and networks, spectral regulations, locations and activities of neighboring radios, policies of the users and/or service providers, and past experience.

The proposed integration of the GRASS-RaPlaT tool into LOG-a-TEC testbed will open possibility to test different hidden node location and transmit power estimation methods in a real environment, by applying known propagation channel models and using measurements at different frequencies for various communication systems. Furthermore, the testbed will open new possibilities to test and validate various innovative cognitive algorithms in real environment.

2.3 Over-the-air reprogramming and experimental data collection

For carrying out the experiments of various UCs, different algorithms need to be implemented and run on the devices of the testbed. In the case of the LOG-a-TEC outdoor testbed, located some 30 km from the JSI campus and coupled with the public lighting infrastructure, remote operation in terms of firmware images transfer, upload to the devices' special storage, programming before the experiment and run during the experiment has to be assured.

Since benchmarking requires reproducible results, the applications ran during experiments have to be uniquely identified and available for rerun. This way, the influence of different implementations on the results can be largely avoided. If possible, the source code necessary to recreate the firmware image should be compiled and linked to a firmware image in a way that allows the study of implementation differences and their effect on the benchmark results. Later on, the source code can be used for further development or reused in the algorithms for new experiments.

Applications can have various configurations' settings, either adjustable before the experiment, or changeable during the experiment. These configuration settings have to be recorded together with other metadata describing the experiment, in order to ensure reproducibility of experiments. Some of the metadata describing a particular configuration includes:

- Identifier of the firmware image running on each of the devices.
- The source code from which the firmware image has resulted.
- Variation of application settings among the devices, where one can additionally distinguish among static settings applied before the start of the experiment and settings that have been changed during the experiment.

Figure 3 depicts how the above described OTA reprogramming functionalities are reflected in the LOG-a-TEC testbed. Since OTA reprogramming represents part of the experiment setup and not the experiment itself, no performance metric is directly related to it.

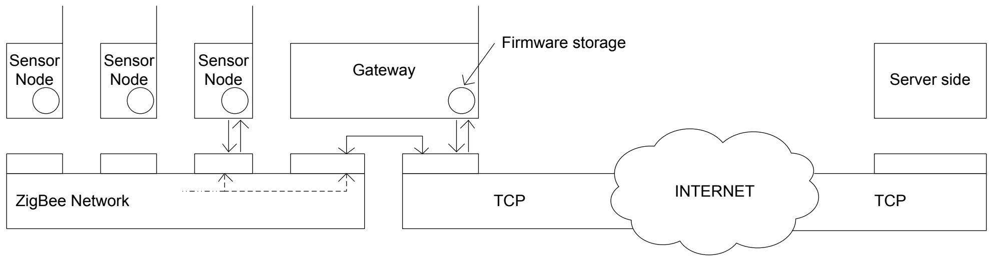

Figure 3. OTA reprogramming in LOG-a-TEC testbed infrastructure

Algorithms and applications that in a particular experiment run on the devices in most cases collect data without major preprocessing. This data has to be transferred from the sensor network infrastructure to a local database, from where it is accessible for further processing. Implementation wise, two principal options for the transmission of data can be distinguished:

- On-line transfer, where the data transmission is performed during the experiment run.
- Off-line transfer, where the data is collected and stored on the device itself during the experiment and only transmitted to the database at the end of the experiment.

These two methods are characterized by the following performance metrics:

- Latency of the communication link between testbed and server side infrastructure, measured in milliseconds. Note that the devices acting as gateways are likely to have smaller latency than others and wireless links cause uncertainty to the latency. Consequently, more appropriate statistical metrics are minimum, average and maximum latency.
- Throughput of the communication links measured in kilobytes per second, which is influenced by the activity of all devices in shared wireless communication channel, so we distinguish between:
    - Peak throughput, describing the data transfer rate achieved between a single transmitting device and the infrastructure.
    - Sustainable throughput, describing the resulting data transfer rate achieved between a device and the infrastructure in the system with multiple transmitting devices.
- Quantity of available measurement storage on a device measured in kilobytes, representing the amount of data that can be saved during the experiment.
- Write cycle speed of the measurement storage, measured in kilobytes per second. This metric gives information about the speed at which data can be saved to the internal memory on the device.
- Percentage of time occupied by the data transmission and not available for the experiment itself. Communication of wireless nodes through the ZigBee network involves transmission on the ISM radio frequency band, which interferes with spectrum sensing or experimental radio traffic.

3. Radio environment sensing for spectrum sharing

The fundamental principle of spectrum sharing is allocation of frequency bands to different technologies, operators or groups of users, that is performed by the regulatory bodies. Additionally, where a particular chunk of spectrum is free to use or shared among several technologies, different channel access schemes are traditionally applied to avoid collisions and interference. But since such spectrum utilization is proving inefficient and technologies are characterized by constantly growing bandwidth requirements, there is a clear demand for spectrum sharing that incorporates real-time knowledge about the radio environment and thereby the context of spectrum occupancy.

Conditions of deployment for US involving context awareness can be split into parameters of spectrum sensing, deployed equipment, which can be modified in case of interchangeable testbed components, and the testbed physical conditions that are largely outside of the experimenter's control.

For all of the UCs described in following sections, radio equipment can be characterized by industry standard metrics for radio receivers:

- Receiver sensitivity – minimum received signal power at the antenna that can be reliably detected over the noise floor of the receiver.
- Receiver adjacent channel power rejection – attenuation of an undesired signal on channels adjacent to the sensing channel.
- Receiver frequency sweep time – the number of channels or a frequency span that can be sensed in a given time interval.
- Antenna gain and radiation pattern in the frequency band of interest.

To enable realistic conditions for experimentation and exploitation of the results, these spectrum sensing characteristics should be comparable or better than what can be expected from cognitive radio devices.

The physical conditions of the testbed include:

- Locations and properties of transmit and receive equipment, their spectrum sensing capabilities and interfering equipment under control.
- Background radio environment characterization. For example, average ISM bands usage patterns from devices that do not belong to the testbed and TV channel usage from broadcasting services.

3.1 Context awareness in the ISM bands

The main goal of experimentation in these bands is detection of interference. In particular, the confidence level for the detection of a particular kind and source of interference is of interest.

3.1.1 Configuration

Nodes in the VESNA-based testbed are capable of narrow-band, energy detection based spectrum sensing in the ISM bands at 433 MHz, 868 MHz and 2.4 GHz. In a particular configuration, nodes can either act as: (i) transmitters of a narrow-band signal, where various modulation formats can be applied; (ii) receivers; or (iii) interferers transmitting a pre-programmed signal.

The spectrum sensing hardware on VESNA node for the ISM bands is for the case of sub-GHz bands based on Chipcon/TI CC1101 [7] and for the 2.4 GHz band on Chipcon/TI CC2500 [8]. Both chips have RF frontends with integrated RSSI narrow-band power detector.

Where needed, receive and transmit capabilities of VESNA nodes will be amended with the USRP radios, capable to transmit/receive wider-band signals.

3.1.2 Performance metrics

RSSI data from sensing devices are processed to obtain a periodogram (received power level vs. frequency and time). In order to characterize the radio environment, these will be compared to the transmitting part that is under the control of the testbed.

3.2 Context awareness in TV licensed bands

Traditionally, large parts of the VHF and UHF frequency bands have been exclusively licensed for use by TV broadcasting service providers and wireless microphones in professional use. With the recent switch from analogue to digital TV broadcasting, however, significant parts of these bands have been freed. Because of the large bandwidth available in these so-called TV white spaces (TVWS) compared to the unlicensed ISM bands, there is a lot of interest in re-using this spectrum for other wireless communications.

With the diminishing use of licensed spectrum the regulatory authorities are starting to permit unlicensed secondary users. However, their use of the spectrum is highly constrained so as to minimize the probability of causing a harmful interference to primary users.

Because of the dynamic nature of TVWS and the limits on the primary user interference re-use of these bands is seen as an opportunity to test and widely deploy novel dynamic spectrum access and cognitive radio technologies.

The goal of spectrum sensing in TV licensed bands is therefore primarily focused on primary user detection. Experiments have to be able to determine the quality metrics of different channel occupancy detection methods, like probability of missed detection and false alarm, range of detection of wireless microphones, benefits of cooperative sensing and combinations of geolocation databases with spectrum sensing methods.

3.2.1 Configuration

A selection of nodes in the VESNA-based testbed is equipped with a custom designed spectrum sensor based on the NXP TDA18219HN silicon tuner [9]. This sensor is capable of performing energy detection sensing at centre frequencies between 42 MHz and 870 MHz with detection bandwidth between 1.7 MHz and 10 MHz. However, the exact range of frequencies, sensitivity and directivity depend on the type of antenna used. These properties enable channel occupancy detection for all currently used TV transmission standards.

In contrast to the ISM bands, individual nodes do not have transmitting capabilities. However, the VESNA-based testbed will comprise portable devices built on the USRP software radio platform which can also be used for transmission in the TV bands. This would for instance allow the experimenter to have a primary frequency band user under control. In case of experiments requiring transmission of signals a test and trial license must first be obtained from the national regulator.

3.2.2 Performance metrics

Context awareness in the licensed TV bands presents special challenges compared to unlicensed ISM bands, due to the required accuracy of the detection of primary users, for which the setup needs to be tested through the probability of false alarm (PFA) and the probability of missed detection (PMD). Primary transmissions present a wide range of powers, with a local broadcast transmitter operating at hundreds of watts while wireless microphones may transmit in the miliwatt range. Additionally, spectrum sensing devices not participating in the cooperative sensing and geolocation databases must outperform primary receivers because they are only estimating the properties of the primary radio channel based on local measurements. This means that receiver equipment metrics, as described in the introduction to this section, represent an essential element of this US.

4. Horizontal sharing between heterogeneous networks in ISM bands

With the ever increasing use of unlicensed ISM bands, technologies to support the coexistence of many end-user wireless devices are of increasing importance and must go beyond the enforced channel access schemes. The distinctive property of the VESNA-based LOG-a-TEC testbed with respect to other testbeds of the CREW federation is its outdoor deployment, characterized by substantially different coexistence problems as the indoor case. From the frequency bands point of view the major equipment is represented by Wi-Fi hotspots, wireless sensor networks as well as some Bluetooth-based devices in the 2.4 GHz frequency band, smart metering (electricity, gas, water, heating) infrastructure in the 868 MHz frequency band, and alarms, door and car keyless entry systems, active RFIDs and other remote control applications for non-line of sight operation in the 433 MHz frequency band.

On one hand, the goal of spectrum sensing in all of the above mentioned ISM frequency bands is to realistically characterize the outdoor environment, whilst on the other hand the aim of the testbed is to enable the study of different coexistence, cooperation and spectrum sharing strategies. The VESNA-based part of the testbed is itself based on a ZigBee wireless sensor network technology. The modules for spectrum sensing or transmission and reception are also based on narrow-band, low-energy radios, thus the focus will be on the algorithms for the use in wireless sensor networks, but coexistence with the available signal sources, such as Wi-Fi and Bluetooth, will also be studied.

4.1 Configuration

Nodes in the testbed will be controlled via a ZigBee network, either at frequency 868 MHz or 2.4 GHz. The VESNA node radio modules for cognitive radio experimentation will be based on Chipcon/TI CC1101 [7] for the 433 MHz and 868 MHz frequency bands and Chipcon/TI CC2500 [8] for the 2.4 GHz frequency band and capable of executing proprietary protocol stacks.

Since the ZigBee-based management network of the testbed may reside on the same frequency band as used for the experimentation, this UC is mostly limited to the off-line data collection, so as to avoid self-imposed interference. In this case an application has to be created for each experiment and run on the devices involved in the experiment autonomously, generating minimal traffic on the infrastructure management network. The consequences of realistic environment, where many uncontrolled interfering signals outside of the experiment may be present, will have to be taken into account by means of appropriate post-processing of the results.

4.2 Performance metrics

The main performance metrics for individual nodes and as an aggregate for the network are:

- packet loss,
- throughput.

Moreover, using the GRASS-RaPlaT tool, with pre-calculated path loss maps of each node that is taking part in the experiment, inverse channel modelling principles will be applied to hidden node detection problem. For this case the main performance metrics are:

- accuracy of hidden node localization,
- transmit power estimation,
- antenna pattern recognition.

5. Cooperation in heterogeneous networks in licensed bands

The switch from analogue to digital TV has created large blocks of spectrum in the VHF and UHF licensed bands that could be used by secondary, unlicensed users. Experiments need to assess the possibility of coexistence between primary and secondary users, where the main concern is decreasing the level of interference to primary users.

5.1 Configuration

A set of nodes in the VESNA-based LOG-a-TEC testbed is capable of spectrum sensing through energy detection in the VHF and UHF frequency bands. In experiments these can serve as spectrum sensors, providing channel occupancy data.

These measurements can then be used in computer simulations to evaluate different spectrum access algorithms. In case a test and trial license for transmission on TV bands can be obtained, data from spectrum sensing nodes can also be used directly in experiments to obtain practical evaluation of the quality of spectrum access algorithms.

VESNA-based testbed also contains devices based on USRP software radio platform that are capable to receive and transmit the signal in the TV band frequencies and can be used as nodes in an experimental TVWS network. Spectrum sensing VESNA nodes can share their sensor data either indirectly through a geolocation database or directly on a cognitive pilot channel in ISM bands.

5.2 Performance metrics

An important metric in heterogeneous networks is the level of interference to primary users caused by secondary transmitters. The level of interference can be characterized for a particular spectrum access algorithm with the following metrics:

- Time to primary user detection – time required for the secondary device to become aware that a primary user has begun using a certain radio channel.
- Probability of missed detection (PMD - false negative) and probability of false alarm (PFA - false positive) – receiver operating characteristics (ROC) show relation between these two probabilities, and by aligning the operating point with other systems present in the CREW federation the results can be compared in an uniform way.
- Time to clear the spectrum – time required for the secondary device to vacate a channel after it has detected a primary user.

6. Conclusions

This deliverable presents the outcome of the review of test configurations and benchmarks as defined in CREW Deliverable D4.1 [1] for the original four CREW testbeds from the perspective of the VESNA-based LOG-a-TEC testbed. It provides the definition of configuration parameters and performance metrics that are of key importance for the reproducibility of the UCs and comparison of results obtained on the same or different testbeds supporting the same US. Reproducibility clearly requires reliable procedures for remote reconfiguration or over-the-air (OTA) reprogramming of the testbed, and experimental data collection. These procedures call for (i) additional configuration parameters to ensure that the software running on the devices can be uniquely identified as well as (ii) new performance metrics that help the users design the experiments.

Benchmarks consist of the wireless scenario including all parameters of the system under test and of the available interference sources used in the experiment. The benchmarks also comprise performance metrics to assess and evaluate the results of experiments in an impartial and comparable manner. Thus, the benchmarks, when fully detailed, only apply to a single very specific UC. To this end, this deliverable provides the baseline framework for experimenters to build benchmarks relevant for the VESNA-based testbed supporting the three USs identified in CREW Deliverable D2.4 [2] (US1, US3 and US4), rather than detailed benchmarks for each of the planned UCs. This framework will be populated with detailed benchmark specifications when the initial trial experiments for individual UCs will be planned, carried out and relevant field experiences will be obtained.

With respect to US1 (context awareness for cognitive networking), the radio environment sensing test configurations and performance measurements have been outlined that will support independent or collaborative spectrum sensing in ISM and TV bands.

As to US3 (horizontal resource sharing in ISM bands), the test configuration and benchmarks specified for VESNA-based testbed are focusing on horizontal spectrum sharing in ISM bands in the outdoor operating environment, with the aim to support investigation and testing of different coexistence, cooperation and spectrum sharing strategies.

Eventually, the test configuration and benchmarks for US4 (cooperation in heterogeneous networks in licensed bands) are primarily focused at reliable characterisation of primary-secondary spectrum usage with VESNA sensor nodes, and subsequent use of these measurements in computer simulations or, if test and trial licence is obtained, in field experiments using USRP software radio platforms as transmitters.

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